

Higgs mixing and diphoton rate enhancement in NMSSM models

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Abstract

We study the implications of the LHC Higgs signals on the Higgs mixing in the next-to-minimal supersymmetric standard model (NMSSM). The Higgs couplings can depart from their values in the standard model (SM) due to mixing effects. However the Higgs signal rate in the WW and ZZ channels can remain close to the SM values, as observed at the LHC, even if the SM-like Higgs boson with a mass near 125 GeV has a large singlet component. This allows to get a sizable enhancement in the Higgs to diphoton rate through the charged-higgsino loop contribution, as well as a sizable reduction of the Higgs to $b\bar{b}$ and $\tau\tau$ rates through the mixing effects, with little deviation in the WW and ZZ signal rates from the SM prediction. We find that an enhancement of diphoton signals by a factor of 1.5 or more, and also a reduction of $b\bar{b}$ and $\tau\tau$ signals by a factor of 0.5, can be obtained in the region of parameter space consistent with the constraints on the higgsino mass parameter and the singlet coupling to the Higgs doublets, which determine the Higgs mixing.

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I. INTRODUCTION

The ATLAS and CMS collaborations have announced the discovery of a Higgs boson near 125 GeV with standard model (SM)-like properties [1, 2]. It is thus of importance to study if models with extended Higgs sector, which is motivated to solve various difficulties of the SM, can accommodate such a SM-like Higgs boson. In this paper we consider the next-to-minimal supersymmetric SM (NMSSM). The NMSSM maintains most of the nice features of the MSSM while allowing richer physics in the Higgs and neutralino sectors since it includes a SM singlet which couples to the Higgs doublets [3].

In the NMSSM, the Higgs boson properties can significantly deviate from the SM ones due to Higgs mixing effects. Meanwhile the observed Higgs signal rate in the WW/ZZ channel, for which experimental uncertainties are small compared to those in other channels, is almost consistent with the SM predictions. This however does not necessarily demand small Higgs mixing, and it turns out that the observed signal rate in this channel can still be explained even if the SM-like Higgs boson has a large singlet component. It is then interesting to examine how the signal rate in other channels are modified when the Higgs boson mixes with the additional neutral scalars in such a way that the WW/ZZ rate remains close to the SM rate.

In particular we pay our attention to the possibility that the observed enhancement in the diphoton rate relative to the SM value, though we need more statistics to confirm this observation, is accommodated in the presence of Higgs mixing effects.^{1,2} Indeed this is achievable through the charged-higgsino loop contribution if the SM-like Higgs boson has a sizable singlet component. In such a case, the mixing effects generally reduce the $b\bar{b}$ and $\tau\tau$ rates below the SM values, because the Higgs couplings to $b\bar{b}$ and $\tau\tau$ are suppressed more

¹ It has been noticed that Higgs mixing effects can increase the diphoton rate above the SM value in the supersymmetric models [4–7], for which case the WW/ZZ rate is also enhanced by a similar amount, assuming that the MSSM superparticles are heavy.

² There have been many works studying how to get a large enhancement in the diphoton signal, see e.g. refs. [8–14] for general discussion. In the supersymmetric SM, charged superparticles can give a sizable contribution to the Higgs coupling to photons if they are light. For instance, in refs. [15–20], light third generation sfermions with large left-right mixing have been considered to achieve this. It is also possible to consider the contribution from light charginos or charged Higgs scalar [21–25]. Alternatively, one may extend the supersymmetric SM to include extra charged-particles with light masses [26–28]. In this case, if colored particles are added, the Higgs production rate at the LHC would be affected significantly.

strongly than those to the W/Z boson and the top quark. On the other hand, the mixing in the neutral Higgs sector depends on the higgsino mass parameter μ and the singlet coupling λ to the Higgs doublets. This implies that the size of mixing effects is subject to the LEP bound on the chargino mass, and the perturbativity limit on λ , as well as to the requirement on the mass of the SM-like Higgs boson. Thus one should consider these, and also other possible constraints on the model parameters, in order to see how large enhancement can be obtained in the diphoton channel through the charged-higgsino contribution. It turns out that an enhancement of diphoton rate, for instance, by a factor 1.5 or larger, as well as a reduction of $b\bar{b}$ and $\tau\tau$ rates by a factor of 0.5, can be achieved while having little deviation in the WW/ZZ rate from the SM value.

This paper is organized as follows. In section II, we will briefly review how the Higgs boson couples to the SM particles when it mixes with other neutral scalars, and then examine the Higgs signal rate. We will focus on the question which mixing angles are allowed for the SM-like Higgs boson whose signal rates in the WW/ZZ channel are close to those predicted by the SM. In section III, we will discuss the possible enhancement of the diphoton rate through the charged-higgsino loop contribution. The constraints on the model parameters will be explored in detail in section IV, where we present some examples to see the mixing effects on the Higgs signal rate in the viable region of parameter space. Section V is devoted to the conclusion.

II. HIGGS SECTOR OF THE NMSSM

In the supersymmetric SM, the properties of the SM-like Higgs boson crucially depend on the mixing in the neutral Higgs sector. So an important question is if it is possible to arrange a SM-like Higgs boson whose properties are consistent with the observation, in the presence of mixing effects. We will see that the Higgs signal rate observed at the LHC can have interesting implications on the Higgs mixing in the NMSSM.

A. Higgs boson with SM-like properties

We start by discussing how to describe the deviation of Higgs properties from the SM behavior. The interactions of a SM-like Higgs boson h at energy scales around 125 GeV can

be examined using the effective action [29],

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & C_V \frac{\sqrt{2}m_W^2}{v} h W_\mu^+ W_\mu^- + C_V \frac{m_Z^2}{\sqrt{2}v} h Z_\mu Z_\mu - C_f \frac{m_\psi}{\sqrt{2}v} h \bar{\psi} \psi \\ & + C_g \frac{\alpha_s}{12\sqrt{2}\pi v} h G_{\mu\nu}^a G_{\mu\nu}^a + C_\gamma \frac{\alpha}{\sqrt{2}\pi v} h A_{\mu\nu} A_{\mu\nu} + \dots, \end{aligned} \quad (1)$$

for ψ denoting the SM fermions, and $v \simeq 174$ GeV. Here the custodial symmetry is assumed for the Higgs couplings to W and Z bosons as suggested by the electroweak precision measurements, and the ellipsis denotes Higgs interactions with non-SM particles. In the SM, the Higgs boson has $C_V = C_f = 1$, while its couplings to gluons and photons are induced only radiatively with the dominant contribution coming from the W -boson and top quark loops.

The Higgs signal rate in the decay channel, $h \rightarrow ii$, relative to the SM prediction is defined by

$$R_h^{ii} = \frac{\sigma(pp \rightarrow h) \text{Br}(h \rightarrow ii)}{\sigma(pp \rightarrow h)|_{\text{SM}} \text{Br}(h \rightarrow ii)|_{\text{SM}}}, \quad (2)$$

where $\sigma(h)$ and $\text{Br}(h \rightarrow ii)$ is the total Higgs production cross section and the branching ratio into the corresponding decay channel, respectively. The production of a SM-like Higgs boson at the LHC is dominated by the gluon-gluon fusion, which receives the main contribution from the top quark loop. Let us assume $C_b = C_\tau$ and $C_t = C_c$, which hold at the tree-level in the MSSM. Then, for $m_h = 125$ GeV, using the well-known production and decay properties of the SM Higgs boson having the same mass, one finds the Higgs signal rate in the WW/ZZ channel to be

$$R_h^{VV} \simeq \frac{(0.94C_g^2 + 0.12C_V^2)C_V^2}{0.64C_b^2 + 0.24C_V^2 + 0.12C_t^2}, \quad (3)$$

under the assumption that new Higgs decay mode if kinematically allowed has a negligibly small decay width. The Higgs signal rate in other channels read

$$\begin{aligned}R_h^{b\bar{b}} &= R_h^{\tau\tau} = \frac{C_b^2}{C_V^2} R_h^{VV}, \\ R_h^{\gamma\gamma} &\simeq \frac{1.52C_\gamma^2}{C_V^2} R_h^{VV}. \end{aligned} \quad (4)$$

In the SM, the Higgs boson has $R_h^{ii} = 1$ by definition. Here one should note that the effective couplings C_g and C_γ receive only loop contributions in the MSSM. For the case that colored

superparticles have masses well above the weak scale, which we will assume in this paper, the effective Higgs coupling to gluons and photons are written as

$$\begin{aligned} C_g &\simeq 1.03C_t - 0.06C_b, \\ C_\gamma &\simeq 0.23C_t - 1.04C_V + \delta C_\gamma|_{\text{SUSY}}, \end{aligned} \tag{5}$$

for h having $m_h = 125$ GeV. The loop correction from charged superparticles, $\delta C_\gamma|_{\text{SUSY}}$, becomes important when they are light.

The above shows that the signal rates for the decay processes relevant to Higgs searches are determined by the effective Higgs couplings C_V , C_t , C_b and $\delta C_\gamma|_{\text{SUSY}}$. We will examine how C_V , C_t and C_b are modified by Higgs mixing effects in the NMSSM, and then move on to discuss how large correction to C_γ is possible from the loops of charged superparticles. In particular, we focus on the possibility to get a large enhancement of the Higgs coupling to photons through the contribution from the charged-higgsino loop, which requires the charged higgsino to have a relatively light mass and also the SM-like Higgs boson to have a sizable singlet component.

B. Higgs boson in the NMSSM

The Higgs boson in the supersymmetric SM can have properties which are significantly deviated from the SM properties due to Higgs mixing effects. In particular, NMSSM models have rich Higgs/neutralino physics as the Higgs sector is extended to include a SM singlet field S . The singlet couples to the Higgs doublets through,

$$W = \lambda S H_u H_d + f(S) + (\text{MSSM Yukawa terms}), \tag{6}$$

so that a higgsino mass parameter is dynamically generated after it gets a vacuum expectation value. The effective Higgs μ and $B\mu$ terms read

$$\begin{aligned} \mu &\equiv \lambda \langle S \rangle, \\ B\mu &\equiv A_\lambda \lambda \langle S \rangle + \lambda \langle \partial_S f \rangle, \end{aligned} \tag{7}$$

where A_λ is the soft SUSY breaking trilinear parameter, and we take a field basis such that a bare μ term if exists is absorbed into S . The superpotential $f(S)$ is necessary to avoid a phenomenologically unacceptable visible axion, and various models are classified according

to its form. In this paper, we do not specify the exact form of $f(S)$, but will assume that there is no CP violation in the Higgs sector. Noting that H_u^0 and H_d^0 mix with the singlet scalar through the scalar potential terms,

$$V_{\text{mix}} = \lambda^2 |S|^2 (|H_u|^2 + |H_d|^2) + (A_\lambda \lambda S H_u H_d + (\partial_S f)^* \lambda H_u H_d + \text{h.c.}), \quad (8)$$

we introduce a mass parameter,

$$\Lambda \equiv A_\lambda + \langle \partial_S^2 f \rangle, \quad (9)$$

for discussion on the Higgs mixing, and will treat μ , $B\mu$ and Λ as independent parameters as $f(S)$ is needed in any model for the Higgs sector not to possess a global symmetry, unless λ is extremely small.

The neutral Higgs sector of the NMSSM has three CP-even Higgs bosons:

$$\begin{aligned} \hat{h} &= \sqrt{2} ((\text{Re} H_d^0 - v \cos \beta) \cos \beta + (\text{Re} H_u^0 - v \sin \beta) \sin \beta), \\ \hat{H} &= \sqrt{2} ((\text{Re} H_d^0 - v \cos \beta) \sin \beta - (\text{Re} H_u^0 - v \sin \beta) \cos \beta), \\ \hat{s} &= \sqrt{2} (\text{Re} S - \langle S \rangle), \end{aligned} \quad (10)$$

where $\langle H_u^0 \rangle = v \sin \beta$ and $\langle H_d^0 \rangle = v \cos \beta$. Among them, \hat{h} behaves exactly like the SM Higgs boson if it does not mix with the others. However, since the mass matrix of the hatted fields is given by

$$\hat{M}^2 = \begin{pmatrix} m_{\hat{h}}^2 & \frac{1}{2}(m_Z^2 - \lambda^2 v^2) \sin 4\beta & \lambda v(2\mu - \Lambda \sin 2\beta) \\ \frac{1}{2}(m_Z^2 - \lambda^2 v^2) \sin 4\beta & m_{\hat{H}}^2 & \lambda v \Lambda \cos 2\beta \\ \lambda v(2\mu - \Lambda \sin 2\beta) & \lambda v \Lambda \cos 2\beta & m_{\hat{s}}^2 \end{pmatrix}, \quad (11)$$

the SM-like Higgs boson generally appears as a mixture of CP-even Higgs bosons:

$$h = c_{\theta_1} c_{\theta_2} \hat{h} - s_{\theta_1} \hat{H} - c_{\theta_1} s_{\theta_2} \hat{s}, \quad (12)$$

which we assume to be the resonance near 125 GeV observed at the LHC. Here $s_\theta = \sin \theta$ and $c_\theta = \cos \theta$, for $-\pi/2 < \theta_i \leq \pi/2$ ($i = 1, 2, 3$) being the mixing angles in the orthogonal matrix diagonalizing \hat{M}^2 (see eq. (25)). There are also two other mass eigenstates, s and H with mass m_s and m_H , respectively, where we define H to be the heaviest Higgs boson and fix the mass of h to be $m_h \simeq 125$ GeV.

Let us summarize the properties of the SM-like Higgs boson in the presence of mixing effects. The Higgs couplings are determined by

$$\begin{aligned} C_V &= c_{\theta_1} c_{\theta_2}, \\ C_t &= c_{\theta_1} c_{\theta_2} + s_{\theta_1} \cot \beta, \\ C_b &= C_\tau = c_{\theta_1} c_{\theta_2} - s_{\theta_1} \tan \beta, \end{aligned} \quad (13)$$

at the tree-level. The branching fraction of h for each decay process deviates from the SM value if the above effective couplings have values different from each other. This is indeed the case due to the second term in the effective coupling to the quarks, which relies on $\tan \beta$ and θ_1 . Note that the sign of θ_1 is also important. For instance, if θ_1 has a positive value, it is possible to reduce the Higgs coupling to the bottom quark relative to the SM value, more significantly than those to the W/Z boson and top quark. This does not happen in the MSSM unless there are large radiative corrections to the mixing between two doublet Higgs bosons. Here we only consider $\tan \beta > 1$ as required for the top Yukawa coupling to remain perturbative at high energy scales. However the situation changes in the NMSSM, where one can consider $\lambda v > m_Z$ for which \hat{M}_{12}^2 is positive, or sizable mixing between the singlet and doublets. As we will see soon, mixing with $\theta_1 > 0$ has an interesting implication for the modification in the Higgs signal rate.

On the other hand, mixing effects on the Higgs boson mass can be examined using the relation,

$$m_h^2 = m_{\hat{h}}^2 - \frac{(s_{\theta_2} s_{\theta_3} - s_{\theta_1} c_{\theta_2} c_{\theta_3})^2}{c_{\theta_1}^2 c_{\theta_2}^2} (m_H^2 - m_{\hat{h}}^2) - \frac{(s_{\theta_2} c_{\theta_3} + s_{\theta_1} c_{\theta_2} s_{\theta_3})^2}{c_{\theta_1}^2 c_{\theta_2}^2} (m_s^2 - m_{\hat{h}}^2). \quad (14)$$

The above relation imposes a constraint on m_H , m_s and the mixing angles because $m_{\hat{h}}$ is restricted to be less than a certain value:

$$m_{\hat{h}}^2 = m_0^2 + (\lambda^2 v^2 - m_Z^2) \sin^2 2\beta, \quad (15)$$

where m_0 is equal to m_Z at the tree-level, and can be regarded as the SM-like Higgs boson mass in the decoupling limit of the MSSM at large $\tan \beta$. The NMSSM contribution raises $m_{\hat{h}}$ above m_0 for $\lambda v > m_Z$, but the amount decreases as $\tan \beta$ increases. Including radiative corrections, one finds [30]

$$m_0^2 = m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2} \ln \left(\frac{m_{\hat{t}}^2}{m_t^2} \right) + \frac{3m_t^4}{4\pi^2 v^2} \left(X_t^2 - \frac{1}{12} X_t^4 \right) + \cdots, \quad (16)$$

where $m_{\tilde{t}}$ is the stop mass, and $X_t = (A_t - \mu \cot \beta)/m_{\tilde{t}}$ denotes the stop mixing parameter. For the stop masses at the TeV scale, m_0 is around 115 GeV. The stop mixing raises m_0 further approximately by the amount, $5 \text{ GeV} \times (X_t^2 - X_t^4/12)$, which is about 5 GeV at $X_t = 1$. The stop mixing contribution is maximized at $X_t = \sqrt{6}$, where m_0 can reach about 130 GeV for stop masses around TeV. In section IV, taking the value of m_0 in the range between 95 and 135 GeV, we will examine in detail the region of parameter space consistent with various constraints on the Higgs mixing.

C. Mixing effects on the Higgs signal rate

The observed Higgs signal rate in the WW/ZZ channel, which has a relatively small experimental error compared to other decay processes, is in good agreement with the SM predictions. However this does not necessarily imply small mixing in the neutral Higgs sector. It is thus of importance to examine the signal rate in other channels when the SM-like Higgs boson has $R_h^{VV} \approx 1$ in the presence of Higgs mixing. The signal rate for $h \rightarrow b\bar{b}$ and $h \rightarrow \gamma\gamma$ are modified according to the relation (4).

Plugging the effective Higgs couplings (13) into the relation (3), we find that Higgs mixing leaves the signal rate R_h^{VV} close to 1 at two different positive values of θ_1 for given $\tan \beta$ and θ_2 . The larger solution of $R_h^{VV} \approx 1$ is approximately given by

$$\theta_1|_{\text{large}} \approx \frac{2.1 - 1.9 \sin^2 \theta_2}{\tan \beta}, \quad (17)$$

for moderate and large values of $\tan \beta$. It is also straightforward to see that the smaller solution reads

$$\theta_1|_{\text{small}} \approx \frac{\tan \beta}{1.4 \tan^2 \beta + 1.7} \sin^2 \theta_2, \quad (18)$$

for $\tan \beta \gtrsim 2$. Thus C_V and C_t are positive for both solutions, while C_b is found to be positive only for $\theta_1|_{\text{small}}$. This results in that the $b\bar{b}$ signal rate can also remain close to the SM value for $\theta_1|_{\text{large}}$ if $C_V \approx -C_b$, which we find the case in the region around $\sin^2 \theta_2 = 0.15$. Note also that the gluon-gluon fusion for the Higgs boson production occurs through the coupling C_g , and thus depends on the relative sign of C_t and C_b since the quarks have masses, $2m_b < m_h < 2m_t$. On the other hand, for the smaller solution $\theta_1|_{\text{small}}$, the SM-like Higgs boson contains non-SM Higgs doublet component whose fraction is much smaller than the singlet fraction. In this case, $R_h^{b\bar{b}}$ is always smaller than R_h^{VV} .

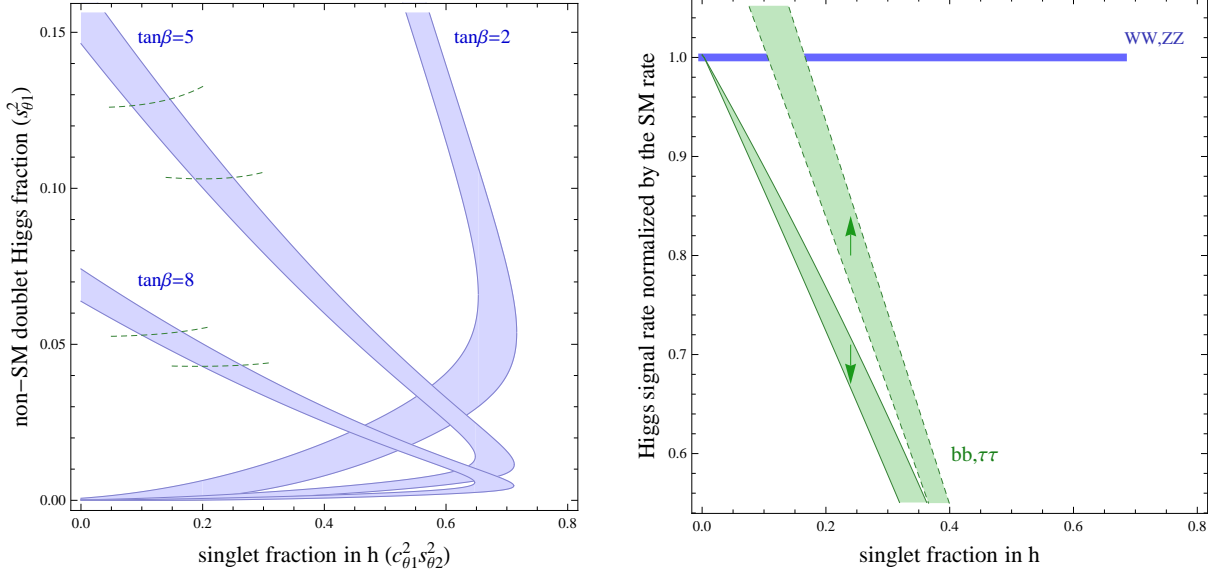


FIG. 1: Mixing effects on the signal rate of the SM-like Higgs boson, $h = c_{\theta_1} c_{\theta_2} \hat{h} - s_{\theta_1} \hat{H} - c_{\theta_1} s_{\theta_2} \hat{s}$ with mass $m_h = 125$ GeV. The left panel shows the region of parameter space where the signal rate in the WW/ZZ channel is $R_h^{VV} = 1 \pm 0.1$, for $\tan\beta = 2, 5, 8$, respectively. The $b\bar{b}$ channel also has $R_h^{b\bar{b}} = 1 \pm 0.1$ in the region between two dashed green lines, in the blue band. The right panel illustrates how the signal rates in $h \rightarrow b\bar{b}$ and $h \rightarrow \tau\tau$ are affected by mixing effects when the Higgs boson has $R_h^{VV} = 1$. The green band is $R_h^{b\bar{b}} (= R_h^{\tau\tau})$ obtained for $2 \leq \tan\beta \leq 5$, where the colored arrow indicates its behavior for increasing $\tan\beta$. The lower (upper) band corresponds to the $b\bar{b}$ rate for θ_1 fixed at the smaller (larger) solution of the equation $R_h^{VV}(\theta_1) = 1$.

Fig. 1 shows the region of parameter space leading to $R_h^{VV} = 1 \pm 0.1$, for $\tan\beta = 2, 5, 8$. One sees that the Higgs signal rate in the WW/ZZ channel can remain consistent with the observation even if the SM-like Higgs boson has a large singlet fraction. In the right panel of the figure, we illustrate how the $b\bar{b}$ and $\tau\tau$ rates are modified when the Higgs mixing leads to $R_h^{VV} = 1$. The green band gives $R_h^{b\bar{b}} (= R_h^{\tau\tau})$ for $2 \leq \tan\beta \leq 5$, where the colored arrow shows how the signal rate changes as $\tan\beta$ increases. The lower (upper) green band corresponds to $R_h^{b\bar{b}}$ for θ_1 fixed at the smaller (larger) solution of the equation $R_h^{VV}(\theta_1) = 1$. The $b\bar{b}$ and $\tau\tau$ rates are reduced relative to the SM case for the smaller solution, however this is not necessarily the case for the other solution. On the other hand, the mixing also affects the diphoton rate, which will be examined in section III by including the contribution from the charged higgsino.

III. ENHANCED DIPHOTON RATE BY HIGGSINO EFFECTS

The Higgs signal in the $h \rightarrow \gamma\gamma$ process has been observed at the rate, 1.5 to 1.8 times larger than the value predicted in the SM. Although the statistics is small yet compared to the WW/ZZ channel, this may be a hint for physics beyond the SM. In particular, it is interesting to see if the observed enhancement of the diphoton rate can be explained within the NMSSM, where the deviation in the WW/ZZ channel is small even if the Higgs mixing is sizable. Indeed the Higgs coupling to photons can receive a significant contribution from the charged-higgsino loop when the Higgs boson has a large singlet component.

Let us examine the higgsino effects on the diphoton rate in the presence of Higgs mixing. Since the singlet scalar couples to the higgsinos through the Yukawa term $\lambda S \tilde{H}_u \tilde{H}_d$ in the NMSSM, the SM-like Higgs boson has the interaction,

$$\mathcal{L} = \frac{\lambda c_{\theta_1} s_{\theta_2}}{\sqrt{2}} h \tilde{H}_u^+ \tilde{H}_d^- + \dots \quad (19)$$

Thus the Higgs coupling to photons is radiatively generated by the charged-higgsino loop. The contribution to C_γ is found to be [29],

$$\delta C_\gamma|_{\text{SUSY}} \simeq -0.17 A_f(\tau_{\tilde{H}^\pm}) \frac{\lambda v}{m_{\tilde{H}^\pm}} c_{\theta_1} s_{\theta_2}, \quad (20)$$

where $\tau_i = m_h^2/4m_i^2$, and the charged higgsino has mass $m_{\tilde{H}^\pm} \simeq |\mu|$ simply assuming that the Wino is heavy so that the mixing in the chargino sector is small. The loop function is given by $A_f(\tau) = 3(\tau + (\tau - 1) \arcsin^2 \sqrt{\tau})/2\tau^2$ for $\tau \leq 1$, and is approximated as $A_f(\tau) \simeq 1 + 7\tau/30$ for small values of τ . On the other hand, the effective couplings C_V , C_t and C_b are negligibly affected by the charged higgsino.

The SM-like Higgs boson can have $R_h^{VV} \approx 1$ for the Higgs mixing (17) or (18), for which the diphoton signal rate will be reduced a bit below the SM value if $\delta C_\gamma|_{\text{SUSY}} = 0$. However, including the radiative correction from \tilde{H}^\pm , the diphoton rate reads

$$R_h^{\gamma\gamma} \simeq \frac{1.52 C_\gamma^2}{C_V^2} R_h^{VV} \simeq \left(1 - 0.28 \frac{s_{\theta_1}}{c_{\theta_1} c_{\theta_2}} \frac{1}{\tan \beta} + 0.21 \frac{s_{\theta_2}}{c_{\theta_2}} \frac{\lambda v}{|\mu|} \right)^2 R_h^{VV}, \quad (21)$$

for $|\mu| \gtrsim 100$ GeV, and thus an enhancement of diphoton signals relative to the SM case is achievable for $R_h^{VV} \approx 1$, when θ_2 is positive. Note that, if $\delta C_\gamma|_{\text{SUSY}} = 0$, the Higgs signal rate in each channel is modified by the mixing effects independently of the sign of θ_2 . To get a large enhancement, the charged higgsino needs to have a small mass. In addition, we need

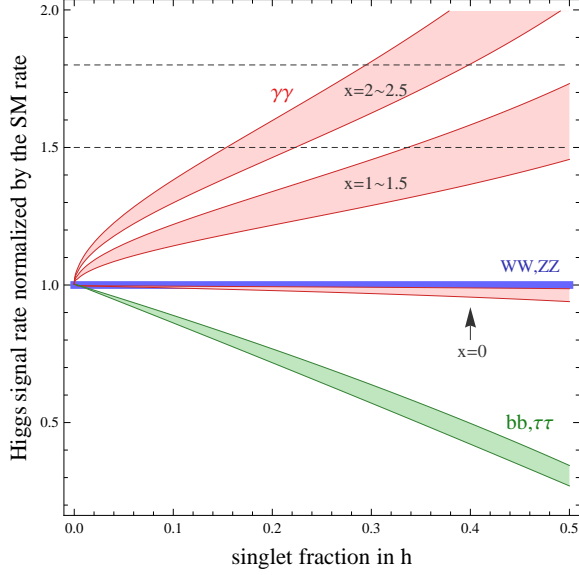


FIG. 2: Enhanced diphoton rate via the charged-higgsino loop contribution, in the presence of Higgs mixing with positive θ_1 and θ_2 . We fix the value of θ_1 at the smaller solution of $R_h^{VV}(\theta_1) = 1$, for which the diphoton rate is determined by θ_2 and $x \equiv \lambda v/|\mu|$, almost independent of $\tan\beta$. The red band corresponds to $R_h^{\gamma\gamma}$ for $x = 0$, $1 \leq x \leq 1.5$, and $2 \leq x \leq 2.5$ from below, respectively. Here we take $2 \leq \tan\beta \leq 8$. The figure also shows the signal rate in other channels, which are rarely affected by the charged-higgsino loop. The green band gives $R_h^{b\bar{b}}$ obtained for $\tan\beta$ in the same range.

a large value of θ_2 , which determines the singlet fraction of the SM-like Higgs boson. Since Higgs mixing with positive θ_1 allows h to contain a large singlet component while having $R_h^{VV} \approx 1$, the second term in the bracket in (21) tells that a small value of θ_1 is favored to have $R_h^{\gamma\gamma}$ larger than R_h^{VV} . For the smaller solution (18) of $R_h^{VV}(\theta_1) \approx 1$, the diphoton rate becomes insensitive to $\tan\beta$, and is written

$$R_h^{\gamma\gamma} \approx \left(1 + 0.21 \frac{s_{\theta_2}}{c_{\theta_2}} \frac{\lambda v}{|\mu|}\right)^2. \quad (22)$$

Thus the signal rate in $h \rightarrow \gamma\gamma$ can be larger than the SM expectation, but still with little deviation in the WW/ZZ channel. The enhancement crucially depends on the value of $\lambda v/|\mu|$, which is less than about 3.5 for $\lambda < 2$ and μ is larger than 100 GeV. In section IV, we will examine the value of $\lambda v/|\mu|$ consistent with various constraints.

Fig. 2 illustrates the effect of the charged higgsino on the diphoton rate, where we have

fixed the value of θ_1 to give $R_h^{VV} = 1$ for positive θ_1 and θ_2 . Among the two solutions of $R_h^{VV}(\theta_1) = 1$, we choose the smaller one, for which the diphoton rate is almost independent of $\tan\beta$. The $R_h^{\gamma\gamma}$ is shown in the red band for $x = 0$, $1 \leq x \leq 1.5$ and $2 \leq x \leq 2.5$, where $x \equiv \lambda v/|\mu|$. In the absence of the charged-higgsino contribution, which is the case with $x = 0$, the diphoton rate is slightly below the SM value. However the higgsino effect can significantly enhance diphoton signals, which demands a large x and sizable singlet fraction in h . For instance, the diphoton rate is about 1.5 times larger than the SM value at $x = 1.2$ if the singlet fraction in h is 0.4. On the other hand, the green band indicates $R_h^{b\bar{b}}$ obtained for $2 \leq \tan\beta \leq 8$. The $b\bar{b}$ rate is reduced relative to the SM value. Meanwhile, one may consider Higgs mixing such that R_h^{VV} is a bit larger than 1. Then the diphoton rate will be increased by the similar amount, whereas $R_h^{b\bar{b}}$ will decrease further.

IV. CONSTRAINTS ON HIGGS MIXING

In this section, we discuss various constraints on the mass spectrum of Higgs bosons and the mixing angles which arise because of their relations to the model parameters in \hat{M}^2 . Then we will consider several examples to explore the region of parameter space where the SM-like Higgs boson has $R_h^{VV} \approx 1$ while satisfying the constraints. The WW/ZZ rate remains close to the SM value at the two solutions of $R_h^{VV}(\theta_1) \approx 1$, among which the smaller one is favored to get a large enhancement in the diphoton rate through the charged-higgsino contribution. So we will focus on the smaller solution, and examine the diphoton rate in the explicit examples.

A. Relation with the Lagrangian parameters

Let us first discuss the constraints on Higgs mixing related to the model parameter μ and λ , which determine the off-diagonal components of \hat{M}^2 . Their values are determined once we fix the mass eigenvalues and mixing angles. This implies that μ and λ are written as functions of

$$\xi \equiv (\tan\beta, m_H, m_s, \theta_1, \theta_2, \theta_3). \quad (23)$$

Meanwhile the LEP bound on the chargino mass requires μ larger than about 100 GeV [31]. In addition, in order for the model to remain perturbative up to at least 10 TeV, λ should be

less than about 2 at the weak scale. For NMSSM models with λ larger than about 0.7 [32], there should appear new physics, such as strong dynamics involving S , at an intermediate scale below the conventional GUT scale $\sim 10^{16}$ GeV. The above bounds on μ and λ translate into the constraints on ξ .

Here we present the relation between ξ and the model parameters appearing in the off-diagonal elements of \hat{M}^2 :

$$\begin{aligned}
\lambda^2 v^2 &= m_Z^2 + \frac{1}{\sin 4\beta} \left((m_H^2 - m_s^2) s_{\theta_2} s_{2\theta_3} + 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2) s_{\theta_1} c_{\theta_2} \right) c_{\theta_1}, \\
\lambda v \mu &= -\frac{1}{4} m_h^2 c_{\theta_1}^2 s_{2\theta_2} - \frac{1}{4} (m_H^2 - m_s^2) s_{\theta_1} c_{2\theta_2} s_{2\theta_3} \\
&\quad + \frac{1}{4} \left((m_H^2 - m_s^2 s_{\theta_1}^2) s_{\theta_3}^2 - (m_H^2 s_{\theta_1}^2 - m_s^2) c_{\theta_3}^2 \right) s_{2\theta_2} \\
&\quad - \frac{\tan 2\beta}{4} \left((m_H^2 - m_s^2) c_{\theta_2} s_{2\theta_3} - 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2) s_{\theta_1} s_{\theta_2} \right) c_{\theta_1}, \\
\lambda v \Lambda &= -\frac{1}{2 \cos 2\beta} \left((m_H^2 - m_s^2) c_{\theta_2} s_{2\theta_3} - 2(m_h^2 - m_H^2 c_{\theta_3}^2 - m_s^2 s_{\theta_3}^2) s_{\theta_1} s_{\theta_2} \right) c_{\theta_1}, \tag{24}
\end{aligned}$$

where we have used that the orthogonal matrix U which diagonalizes \hat{M}^2 is parameterized in terms of three mixing angles,

$$U = \begin{pmatrix} c_{\theta_1} c_{\theta_2} & -s_{\theta_1} & -c_{\theta_1} s_{\theta_2} \\ s_{\theta_1} c_{\theta_2} c_{\theta_3} - s_{\theta_2} s_{\theta_3} & c_{\theta_1} c_{\theta_3} & -c_{\theta_2} s_{\theta_3} - s_{\theta_1} s_{\theta_2} c_{\theta_3} \\ s_{\theta_1} c_{\theta_2} s_{\theta_3} + s_{\theta_2} c_{\theta_3} & c_{\theta_1} s_{\theta_3} & c_{\theta_2} c_{\theta_3} - s_{\theta_1} s_{\theta_2} s_{\theta_3} \end{pmatrix}, \tag{25}$$

for $c_\theta = \cos \theta$ and $s_\theta = \sin \theta$.

B. Higgs boson mass

There are also constraints related to the mass spectrum of the Higgs bosons. The SM-like Higgs boson has a mass which is written as a function of m_0 and ξ , as is given by (14). Thus, requiring $m_h \simeq 125$ GeV constrains the parameter space of m_0 and ξ . Here the value of m_0 has an upper bound, crucially depending on the radiative corrections. For instance, m_0 is less than about 120 GeV for the stop with mass around or smaller than 1 TeV and small stop mixing. One can also arrange m_0 around or larger than 130 GeV by considering stop masses above a few TeV or invoking large stop mixing. It is worth noting that, in the NMSSM, m_0 can receive an additional sizable contribution from the higgsino loops. The superpotential $f(S)$ provides mass to the singlino, $m_{\tilde{S}} = \langle \partial_S^2 f \rangle$. If $m_{\tilde{S}}$ is around or below μ ,

the interactions

$$-\mathcal{L}_{\text{int}} = \lambda H_u \tilde{H}_d \tilde{S} + \lambda H_d \tilde{H}_u \tilde{S} + \mu \tilde{H}_u \tilde{H}_d + \frac{1}{2} m_{\tilde{S}} \tilde{S} \tilde{S} + \text{h.c.} \quad (26)$$

will remain relevant at low energy scales. Then the mass of \hat{h} receives additional radiative corrections, analogously to that from the top Yukawa coupling. The correction is estimated naively to be [33]

$$\delta m_0^2 \approx \frac{\lambda^4 v^2}{4\pi^2} \ln \left(\frac{m_s^2}{|\mu|^2} \right), \quad (27)$$

for $m_s^2 \gg |\mu|^2$. The above contribution is quite sensitive to λ , but is almost independent of $\tan \beta$. In the analysis, we will consider $95 \text{ GeV} \leq m_0 \leq 135 \text{ GeV}$, while keeping in mind that larger values can be allowed depending on models.

On the other hand, the experimental constraints from the $b \rightarrow s\gamma$ process require the charged Higgs scalar to be heavier than about 350 GeV [34] unless there are cancellations with superparticle contributions. The charged Higgs scalar obtains a mass according to $m_{H^\pm}^2 = m_{\hat{H}}^2 + m_W^2 - m_Z^2 \sin^2 2\beta$ at the tree-level, while $m_{\hat{H}}^2$ is given by

$$m_{\hat{H}}^2 = s_{\theta_1}^2 m_h^2 + c_{\theta_1}^2 c_{\theta_3}^2 m_H^2 + c_{\theta_1}^2 s_{\theta_3}^2 m_s^2, \quad (28)$$

implying that an addition constraint will be imposed if one requires a large value of m_{H^\pm} to avoid the constraint from $b \rightarrow s\gamma$.

For a large value of m_H , the mixing angle θ_3 needs to be small since otherwise mixing between \hat{h} and \hat{H} will decrease the mass of the SM-like Higgs boson significantly. Suppose that θ_3 is similar to or smaller than θ_1 in size. Then the Higgs mass reads

$$m_h^2 \approx m_{\hat{h}}^2 - \frac{1}{\tan^2 \beta} \frac{s_{\theta_2}^4}{1 - s_{\theta_2}^2} (m_H^2 - m_{\hat{h}}^2) - \frac{s_{\theta_2}^2}{1 - s_{\theta_2}^2} (m_s^2 - m_{\hat{h}}^2), \quad (29)$$

for $\theta_1 = \theta_1|_{\text{small}}$, where the coefficients of order unity have been neglected in the last two terms. We see that the second term, which is a result of mixing between two doublet Higgs bosons, is much suppressed compared to the third term. Indeed one can find that the second term lowers the mass of h by less than about 10 GeV even for H having mass around or above 350 GeV, if

$$s_{\theta_2}^2 \lesssim 0.15 \times \left(\frac{m_H}{350 \text{ GeV}} \right)^{-1} \tan \beta. \quad (30)$$

for $\tan \beta \gtrsim 2$. On the other hand, the third term arises due to mixing with the singlet, and can have either sign. This contribution will compensate the mass decrease by the second

term if s has a mass smaller than $m_{\hat{h}}$. The relation $m_{\hat{h}}^2 = m_0^2 + (\lambda^2 v^2 - m_Z^2) \sin^2 2\beta$ tells that the sign of the third term depends m_0 , λ and $\tan \beta$. It is clear that m_s much larger than m_0 will make it difficult to get $m_h \simeq 125$ GeV unless the NMSSM contribution to $m_{\hat{h}}$ is large enough.

Let us discuss further the properties of s , which is singlet-like in most of the parameter space of interest. Since it couples to the SM particles through the doublet Higgs components, it may be possible to detect s at hadron colliders when Higgs mixing is large. The production and decay rate of s depend on its mass and the fraction of the Higgs doublets. However, if the invisible decay into neutralinos is kinematically allowed, the discovery of the singlet-like Higgs boson will become very difficult. This is the case for $m_h < 2m_{\chi_1^0} < m_s$, where the lower bound on $m_{\chi_1^0}$ would be necessary to suppress the invisible decay of the SM-like Higgs boson.³ On the other hand, if $m_s < m_h$, one should take into account the LEP constraints on the signal rate of s in $e^+e^- \rightarrow Zs \rightarrow Zb\bar{b}$ [38]. In this case, it may still be possible to have sizable mixing if m_s lies in the range between about 90 and 110 GeV.

Before proceeding to the analysis, we briefly mention about the property of the lightest neutralino, which we assume the lightest superparticle (LSP). For $\lambda v/|\mu|$ around one, the lightest neutralino χ_1^0 is a sizable mixture of the neutral higgsinos and singlino, simply assuming that all the gauginos are heavy. If χ_1^0 is heavier than the W -boson, the annihilation among LSPs takes place with a large cross section, dominantly through the t -channel charged-higgsino exchange with W bosons in the final state. Then thermal relic density of χ_1^0 would be too small to account for the observed dark matter density. To avoid this, one may consider light gauginos so that χ_1^0 has a sizable Bino component. Another way would be to implement non-thermal production of LSPs, or to consider the QCD axion as a dark matter.

On the other hand, for $m_{\tilde{s}} \gg |\mu|$ and $\lambda v/|\mu|$ around one, the mixing decreases the mass of a higgsino-like neutralino, and thus it is possible to have χ_1^0 lighter than m_W but heavier than $m_h/2$. In such a case, the annihilation via the s -channel Z -boson exchange into SM fermions is not so effective due to the suppressed $Z\chi_1^0\chi_1^0$ coupling, and the coannihilation effect [39] is also suppressed because the charged-higgsino still has a mass equal to μ . However, since the

³ In models where $f(S)$ contains only a linear term of S [33, 35–37], the singlino has no Majorana mass term, and the mass and the coupling to h of χ_1^0 are proportional to $\lambda^2 v \sin 2\beta/\mu$. One would thus need small $\tan \beta$ and large λ to kinematically forbid the invisible decay of h into neutralinos.

$h\chi_1^0\chi_1^0$ coupling can be sizable in the NMSSM, it would be possible to get the correct dark matter density from thermally produced LSPs. A detailed analysis will be given elsewhere.

C. Examples

We have discussed the constraints and the favored values of model parameters. Let us now examine the diphoton rate in the region of parameter space where such requirements are satisfied. In the analysis, we impose the constraints,

$$m_h \simeq 125 \text{ GeV}, \quad |\mu| \geq 105 \text{ GeV}, \quad \lambda \leq 2, \quad (31)$$

by taking m_0 in the range

$$95 \text{ GeV} \leq m_0 \leq 135 \text{ GeV}. \quad (32)$$

For given m_H , m_s and θ_3 , three parameters of ξ in (23) remain unfixed. Among them, θ_1 is fixed if one requires the signal rate in the WW/ZZ channel to be close to the SM value. Then we can examine the above constraints by scanning over $\tan\beta$ and θ_2 , or equivalently in terms of $\tan\beta$ and the singlet fraction in the SM-like Higgs boson. The Higgs signal rate in $h \rightarrow \gamma\gamma$ is determined by $x = \lambda v/|\mu|$ and the singlet fraction in h .

In Fig. 3, we show the diphoton rate relative to the SM value in the region of parameter space allowed by the requirements mentioned above, for two examples,

$$\text{example 1 : } (m_H, m_s, \theta_3) = (480 \text{ GeV}, 160 \text{ GeV}, 0.10),$$

$$\text{example 2 : } (m_H, m_s, \theta_3) = (780 \text{ GeV}, 160 \text{ GeV}, 0.07),$$

with θ_1 fixed at the smaller solution of $R_h^{VV}(\theta_1) = 1.05$. For both examples, the parameter space is mainly constrained by the requirements, $m_h = 125 \text{ GeV}$ and $|\mu| \geq 105 \text{ GeV}$. The right side of the blue-dashed curve gives μ larger than 105 GeV, and h has $m_h = 125 \text{ GeV}$ between two red-dashed curves if one considers $95 \text{ GeV} \leq m_0 \leq 135 \text{ GeV}$. The gray-shaded region is excluded since $\lambda^2 < 0$. The diphoton rate relative to the SM value is shown in black lines. We see that an enhancement by a factor of 1.5 or larger can be accommodated through the charged-higgsino contribution, when $\tan\beta$ is about 2 – 3 and the singlet fraction in h is larger than 0.39 in the left panel. For the other example, this is achieved at $3 \lesssim \tan\beta \lesssim 4.8$ when the singlet fraction in h is larger than 0.26. On the other hand, the mixing effects reduce the $b\bar{b}$ rate below the SM value.

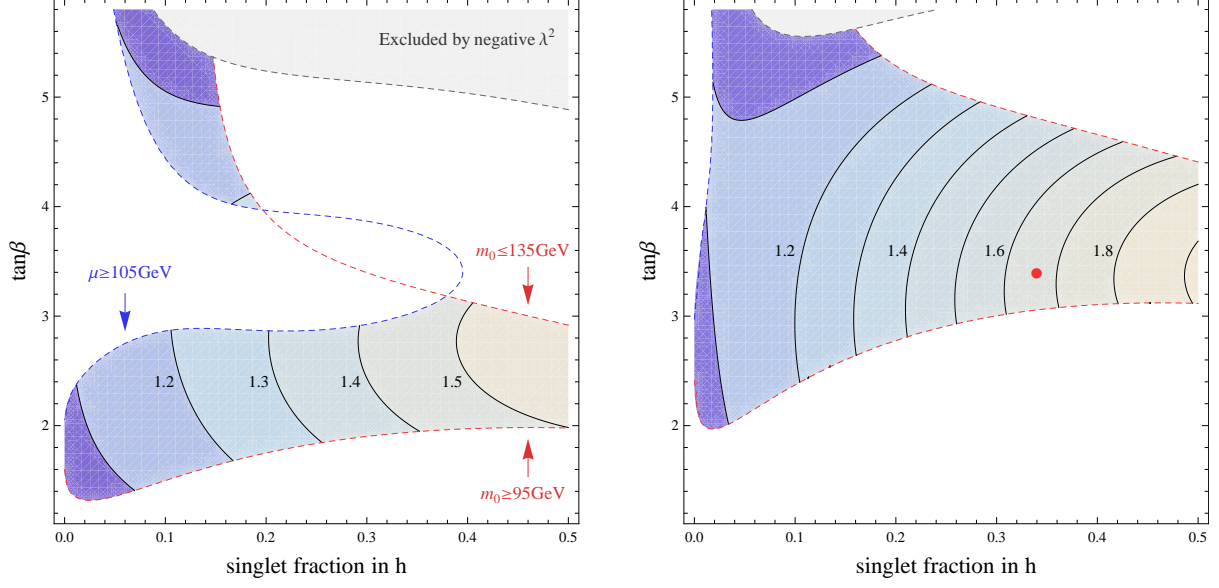


FIG. 3: Enhanced diphoton rate in the region of parameter space allowed by $|\mu| \geq 105$ GeV and $\lambda \leq 2$, where we have fixed θ_1 at the smaller solution of $R_h^{VV}(\theta_1) = 1.05$. The left panel is for the case with $(m_H, m_s, \theta_3) = (480 \text{ GeV}, 160 \text{ GeV}, 0.1)$, while the right one is for $(m_H, m_s, \theta_3) = (780 \text{ GeV}, 160 \text{ GeV}, 0.07)$. In both figures, μ is larger than 105 GeV in the right side of the blue-dashed curve, and $m_h = 125$ GeV is obtained for $95 \text{ GeV} \leq m_0 \leq 135 \text{ GeV}$ in the region between two red-dashed curves. The gray-shaded region is excluded due to negative λ^2 . The contours of $R_h^{\gamma\gamma}$ are indicated by black lines, with the contour interval equal to 0.1. To see the detailed Higgs properties, we take an example point as given by the red-filled circle.

To see the relation between ξ and the model parameters, we take an example point at

$$(\tan \beta, m_H, m_s, \theta_1, \theta_2, \theta_3) = (3.4, 780 \text{ GeV}, 160 \text{ GeV}, 0.07, 0.62, 0.07), \quad (33)$$

which corresponds to the red-filled circle in the figure. The above set of parameters translates into

$$(\lambda, \mu, \Lambda, m_0) \simeq (1.03, 112 \text{ GeV}, 376 \text{ GeV}, 110 \text{ GeV}), \quad (34)$$

together with $m_{\hat{H}} \simeq 776$ GeV and $m_{\hat{s}} \simeq 167$ GeV. The Higgs signal rate in the WW/ZZ channel is $R_h^{VV} = 1.05$ at the example point, and the $b\bar{b}/\tau\tau$ channel has $R_h^{b\bar{b}} = R_h^{\tau\tau} \simeq 0.51$. Finally, the diphoton rate is found to be $R_h^{\gamma\gamma} \simeq 1.66$, as a result of the charged-higgsino loop contribution combined with the Higgs mixing effects.

V. CONCLUSIONS

We have examined how to arrange a SM-like Higgs boson in the NMSSM, in a way consistent with the LHC results on the Higgs boson search. The observed WW/ZZ signal rate can be compatible with the model even when the SM-like Higgs boson has a large singlet component. This leads to an interesting possibility that the Higgs to diphoton signal rate is enhanced by the loops of charged higgsino which couples to the SM-like Higgs boson through mixing with the singlet scalar. A large enhancement is achievable when there is a large singlet fraction in the SM-like Higgs boson and the charged higgsino is light.

The Higgs mixing depends on the higgsino mass parameter μ and the singlet coupling λ to the Higgs doublets. Hence there are constraints on the Higgs mixing angles coming from the LEP bound on the chargino mass, and the perturbativity limit on λ . In addition, the model should provide a mass near 125 GeV to the SM-like Higgs boson. Taking into account these constraints, we find that the charged-higgsino loop contribution, combined with the mixing effects, can enhance the diphoton signal rate above the SM expectation by a factor of 1.5 or more, while having little deviation in the WW/ZZ rate.

On the other hand, the Higgs mixing effects reduce the $b\bar{b}$ and $\tau\tau$ signals below the SM values, if the mixing between two doublet Higgs bosons \hat{h} and \hat{H} is relatively small, which is favored to get a sizable enhancement of the diphoton signal rate while keeping the WW/ZZ rate similar to the SM prediction. Indeed we could see that the $b\bar{b}$ and $\tau\tau$ rates can be reduced by a factor of 0.5, or even less, for the mixing parameters which would enhance the diphoton signal by a factor of 1.5.

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